Electrohydrodynamic (EHD) Enhancement of Boiling Heat Transfer of R113+WT4% Ethanol

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Nucleate boiling heat transfer for refrigerants, R113, and R113+wt4% ethanol mixture, an azeotropic mixture under electric field was investigated experimentally in a single-tube shell/tube heat exchanger. A special electrode configuration which provides a more uniform electric field that produces more higher voltage limit against the dielectric breakdown was used in this study. Experimental study has revealed that the electrical charge relaxation time is an important parameter for the boiling heat transfer enhancement under electric field. Up to 1210% enhancement of boiling heat transfer was obtained for R113+wt4% ethanol mixture which has the electrical charge relaxation time of 0.0053 sec whereas only 280% enhancement obtained for R113 which has relaxation time of 0.97 sec. With artificially machined boiling surface, more enhancement in the heat transfer coefficient in the azeotropic mixture was obtained.

Key Words: Azeotropic Mixture, EHD, Electrical Charge Relaxation Time,
Nucleate Boiling

Nomenclature

\[ A \] : Heat transfer area, \( m^2 \)
\[ C_p \] : Specific heat of water, \( \text{kJ/kgK} \)
\[ D_b \] : Bubble diameter, \( m \)
\[ E \] : Electric field strength, \( \text{N/C} \)
\[ f_b \] : Frequency of bubble departure, \( 1/s \)
\[ g \] : Gravitational acceleration, \( m/s^2 \)
\[ h \] : Heat transfer coefficient, \( \text{W/m}^2\text{K} \)
\[ I \] : Current, \( A \)
\[ \dot{m} \] : Mass flow rate of water inside tube, \( \text{kg/s} \)
\[ P \] : Pressure
\[ \dot{Q} \] : Heat flow rate, \( \text{kJ/s} \)
\[ \text{Re} \] : Reynolds number
\[ R_m \] : Weighting factor defined by Eq. (4)
\[ T \] : Temperature, \( \text{K} \)
\[ T_{av} \] : Average temperature of tube wall, \( \text{K} \)
\[ V \] : Voltage

Greek letters
\[ \varepsilon \] : Permittivity constant, \( \text{C}^2/\text{N}^2\text{m}^2 \)
\[ \rho \] : Density, \( \text{kg/m}^3 \)
\[ \sigma \] : Surface tension, \( \text{N/m} \)
\[ \tau_b \] : Bubble departure time
\[ \tau_e \] : Electrical charge relaxation time

Subscripts
\[ E \] : Electric field
\[ l \] : Liquid
\[ o \] : Zero field
\[ \text{sat} \] : Saturated state
\[ v \] : Vapor
\[ \text{wi} \] : Water stream at the inlet of tube
\[ \text{wo} \] : Water stream at the outlet of tube

1. Introduction

For utilizing low temperature waste heat source,
one of major tasks is to develop high performance heat exchanger. Especially compact evaporator is an important thermal component for the plants such as Organic Rankine Cycle engine and large scale heat pumps. Electrohydrodynamic (EHD) augmentation (Cooper, 1990) has been proved to be one of the most appropriate techniques to enhance nucleate boiling heat transfer in dielectric liquids which are suitable working fluids for the evaporator employed in waste heat recovery plants.

Previous experiments of EHD enhancement in boiling heat transfer have been done mainly on the film boiling regime (Choi, 1960; Markels and Durfee, 1964), where dramatic increase in heat transfer rate occurs. Such great enhancement is known to be due to the film destabilization caused by electrical forces acting on the vapor–liquid interface (Johnson, 1968). Fundamental research was done to investigate the nucleation mechanism in a cavity under an electric field (Cooper, 1990) and how the dielectrophoretic force due to the difference between the dielectric permittivity of the liquid and vapor phases in a nonuniform electric field (Bonjour and Verdier, 1960) affects the bubble behavior near the boiling surfaces, which in turn promotes the heat transfer rate. EHD enhancement up to a factor of ten has been obtained from a lo-fin tube with complete elimination of boiling hysteresis (Cooper, 1990). The disturbance of heat transfer layer due to the buoyancy driven motion of bubble trapped in weak field region of the lo-fin tube (Cooper, 1990; Han et al., 1999) was reported to be a cause which bring such dramatic enhancement in nucleate boiling heat transfer.

One of the common findings from the previous investigations on EHD enhancement of nucleate boiling is that the number of bubble increases while the diameter of bubble decreases as the electric field increases (Basu, 1973; Cooper, 1990; Kawahira et al., 1990; Ohadi et al., 1992). Another interesting observation from previous experiments is the bubble coalescing on the lower part of heat transfer tube surrounded by six wire electrodes with equal spacing (Kawahira et al., 1990; Ohadi et al., 1992; Seyed–Yagoobi et al., 1996). Proper electrode configuration for the case of employing wire electrodes around the heat transfer tube is required to induce buoyancy driven bubble motion which, in turn, enhance the boiling heat transfer (Oh and Kwak, 2000). However it has been found that the relaxation time of electrical charge of liquid is also one of crucial parameters to determine the influence of the electric field on the bubble behavior (Ogata et al., 1992). That is, if the relaxation time is much longer than the bubble detachment period, which is the case of FC–72, the bubble behavior is not affected by presence of the electric field at all (Han et al., 1999). Investigation of flow boiling in an annular channel under applied dc electric field which causes a flow regime redistribution was also done (Bryan and Seyed–Yagoobi, 2000; Cotton et al., 2005).

In this study, the effect of dc electric field on nucleate boiling heat transfer for refrigerants, R113, and R113+wt4% ethanol mixture, an azeotropic mixture was investigated experimentally by using a single tube shell/tube heat exchanger. Wide range of the wall superheat for boiling action was controlled by the temperature of the water flowing inside tube. For working fluids, R113, and R113+wt4% ethanol mixture which have quite different charge relaxation time in order of magnitude scale were chosen. Effect of the wall superheat and applied electric field strength on the nucleate boiling heat transfer were tested in this study. Also the nucleate boiling heat transfer coefficient in the azeotropic mixture with an artificially machined tube was measured.

2. Experimental Apparatus and Procedures

2.1 Experimental apparatus

A schematic diagram of the EHD augmentation boiling heat transfer unit is shown in Fig. 1. The experimental unit consists of a single tube shell/tube evaporator ①, condensers ②, ③, constant temperature bath circulator ②, hot water storage tank ④, and high voltage supplier ⑥. The evaporator shell was made of stainless steel pipe of 150 mm inside diameter with two 125 mm diame-